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RESEARCH MEMORANDUM

MEASUREMENT AND CALCULATION OF BLADE TORSIONAL

DEFLECTION OF THREE SUPERSONIC-

TYPE PROPELLERS

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SUMMARY

An investigation to determine the blade torsional deflection of three supersonic-type propellers at various operating conditions has been conducted on the NACA 6,000-horsepower propeller dynamometer in the Langley 16-foot transonic tunnel and at the Langley propeller static test stand. The propellers tested in the tunnel were the Curtiss-Wright 109622 (3 blades, 9.75-foot diameter) and the WADC-Aeroproducts propeller (3 blades, 12-foot diameter). Blade torsional deflection was measured for these propellers at the 0.75 radial station at forward Mach numbers up to 0.96 and rotational speeds up to 2,100 rpm at several blade angles. The NACA 10-(3)(049)-03 two-blade propeller was tested at the Langley propeller static test stand at zero advance for blade angles of $0°$, $4°$, $8°$, and $12°$ (measured at the 0.75 radial station) at rotational speeds up to 1,800 rpm. Blade torsional deflection of this propeller was measured at the 0.70 radial station.

The results of the investigation indicate that the blade-torsional deflection of supersonic-type propellers can be appreciable, but can be predicted by theory with good accuracy. Propellers having thin blade sections experience an increased torsional stiffening effect as indicated by theory. A comparison of calculated and measured values of blade torsional deflection for the Curtiss-Wright propeller indicated that the aerodynamic twisting moment about the flexural axis was negligible when a majority of the propeller-blade sections were operating at supersonic speeds.

Calculations of blade torsional deflection for the WADC-Aeroproducts propeller indicate that for an off-design condition of operation, for instance, the propeller operating as a brake, blade torsional deflection can be several times the value of the design condition of operation.

INTRODUCTION

In the design of a supersonic-type propeller aerodynamic considerations dictate use of thin blade sections. However, propellers having thin sections also have a low value of torsional rigidity and are susceptible to blade torsional deflection (or blade twist). To assure attainment of maximum efficiency at the design condition of operation, a knowledge of the magnitude of the blade torsional deformation while operating is important so that it can be included in the blade design.

Previous optical measurements of blade twist (ref. 1) for propellers thicker than the present supersonic-type propellers indicated blade twist was not negligible but could be computed with good accuracy.

The object of the present investigation was to measure the magnitude of the blade twist for supersonic-type propellers and ascertain whether blade twist could be accurately predicted by theory. It was also desirable to determine whether thin propeller blades experience an increase in torsional stiffness greater than that obtained from membrane analogy as indicated in reference 2.

The scope of the present paper is not confined to a specific case of propeller operation, but through analysis and application of measured and calculated values of blade twist for the three propellers tested, the entire propeller operating range is encompassed. In the analysis, the relative magnitude of blade twist for the different operating conditions and the effect of blade twist on the aerodynamic and flutter characteristics of a propeller are noted.

The propellers tested are the Curtiss-Wright 109622, the WADC-Aeroproducts, and the NACA 10-(3)(049)-03. The first two propellers mentioned were tested in the Langley 16-foot transonic tunnel at forward Mach numbers up to 0.96 and rotational speeds to 2,100 rpm. The NACA 10-(3)(049)-03 propeller was tested at the Langley propeller static test stand at zero advance for rotational speeds up to 1,800 rpm. Blade twist was measured at the 0.75 radial station for the WADC-Aeroproducts and Curtiss-Wright propellers and at the 0.70 radial station for the NACA 10-(3)(049)-03 propeller.

SYMBOLS

b blade chord, ft

c angle from bottom dead center to reference prism location at which light is reflected to photoelectric cell, deg (fig. 5)

c_{l_d} blade-section design lift coefficient

C_P power coefficient, $P/\rho n^3 D^5$

C_T thrust coefficient, $T/\rho n^2 D^4$

$\dfrac{dC_P}{dx}$ power-coefficient loading

$\dfrac{dC_T}{dx}$ thrust-coefficient loading

D propeller diameter, ft

E Youngs' modulus of elasticity, lb/sq ft

G shear modulus of elasticity, lb/sq ft

h blade-section maximum thickness, ft

J advance ratio, V/nD

J' torsional-stiffness constant (based on membrane theory), ft^4

J_T' total torsional-stiffness constant for 16-series sections,

$$J'\left[1 + 0.0145 \frac{E}{G}\left(\frac{b}{h}\right)^2 b^2\left(\frac{d\beta}{dr}\right)^2\right], \ ft^4 \quad (ref. 2)$$

M Mach number of advance

M_a aerodynamic torsional moment, ft-lb

M_c tensile torsional moment, ft-lb

M_p planipetal torsional moment, ft-lb

M_t propeller tip Mach number

N propeller rotational speed, rpm

n propeller rotational speed, rps

P   power, ft-lb/sec

R   propeller-tip radius, ft

r   radius to a blade element, ft

T   thrust, lb

t   time difference between signal from reference prism
            and signal from prism on propeller blade, sec

V   velocity of advance, fps

x   fraction of tip radius, r/R

y   distance from propeller rotational axis to horizontal
            plane through light source, ft (fig. 5)

z   horizontal distance from light source to plane of
            rotation of propeller, ft (fig. 5)

β blade angle, deg

$\beta_{0.75R}$ static blade angle at 0.75 radial station, deg

$\Delta\beta$ torsional deflection, deg

ρ air density, slugs/cu ft

ϕ_{0} geometric helix angle, $\tan^{-1} \dfrac{J}{\pi x}$, deg

Subscripts:

0   reference or zero operating condition

1   any operating condition other than the reference condition

x   fraction of tip radius, r/R

APPARATUS

Test facilities.- The Curtiss-Wright 109622 propeller and the WADC-
Aeroproducts propeller were tested in the Langley 16-foot transonic
tunnel. The operational and flow characteristics of the tunnel are

given in reference 3. When the dynamometer and cylindrical body were installed in the test section, the axial Mach number distribution (as shown in fig. 1) differed from that given in reference 3. A description of the airstream calibration and the results obtained with the dynamometer and cylindrical body installed in the 16-foot transonic tunnel are given in reference 4.

The NACA 10-(3)(049)-03 propeller was tested at zero advance at the Langley propeller static test stand.

Dynamometer.- For the wind-tunnel tests the two 3,000-horsepower units of the dynamometer were coupled in tandem with the propeller installed on the forward unit. A long cylindrical body extended from a point upstream of the minimum-area section of the tunnel to the propeller spinner (fig. 1). The cylindrical body was placed upstream of the spinner to produce a radially uniform axial flow field at the propeller plane. The arrangement of the dynamometer and cylindrical body in the wind-tunnel test section is shown in figure 1 and a photograph is shown in figure 2. A complete description of the 6,000-horsepower dynamometer is given in reference 5.

For the tests at the Langley propeller static test stand, only one unit of the dynamometer was used. A photograph of the static-test-stand installation is given in figure 3.

Optical deflectometer.- Propeller-blade torsional deflection was measured by means of an optical deflectometer. The essential components of the deflectometer are a concentrated arc light source, a photoelectric cell, a propeller-blade prism, a reference prism, and an electronic counter. A complete description and operating procedure for the optical deflectometer are given in reference 6 and a sketch (fig. 4) shows the arrangement of some of the components of the deflectometer inside a protective fairing which was mounted at the base of the front-unit dynamometer support strut. The following brief description as to how the deflectometer operated is given to permit an understanding of modifications made to the deflectometer for the wind-tunnel tests.

Light from the concentrated source is reflected from a prism mounted on the propeller blade and from a reference prism on the hub (or spinner) to the sensitive portion of a photoelectric cell. At the photoelectric cell the light signals are converted to electrical signals, amplified, and then fed into an electronic counter which measures the time difference between the two signals. Blade twist can be determined at a given propeller operating condition when the following are known: time difference between the propeller blade prism signal and the reference prism signal, propeller rotational speed, and the position of the photoelectric cell from the plane of rotation and the axis of rotation.

For the wind-tunnel tests it was found necessary to modify the static-test-stand version of the instrument (ref. 6). A separate light source and photoelectric cell were needed for the reference prism to insure a high-intensity reflected spot of light at the photoelectric cell. Preliminary tests using only one light source to cover both the propeller-blade prism and the reference prism produced a low-intensity reflected spot of light at the photoelectric cell which in turn produced a weak electrical signal. This weak signal could not be detected at high tunnel-noise levels. A schematic diagram (fig. 5) shows the location of the deflectometer components for the wind-tunnel tests.

Operation of the optical deflectometer at the Langley propeller static test stand, prior to the tunnel tests, aided in the development of the instrument. However, there were problems that occurred during the tunnel tests that seriously limited the reliability of the instrument and consequently prevented obtaining complete blade-twist data for all the propeller tests. Vibration due to tunnel operation at high speeds was the major obstacle that prevented obtaining complete data. Eventually the components inside the protective fairing were isolated in a manner that helped reduce the effect of vibration.

Propellers.- The important geometrical properties of the three propellers tested are given in the following table and the radial variation of h/b, b/D, and β is shown in figure 6:

Propeller	Diameter, ft	Number of blades	Blade section	Plan form	Thickness ratio
Curtiss-Wright 109622	9.75	3	Solid steel NACA 16-series symmetrical	Rectangular (14-in. chord)	$h/b = 0.06$ at $x = 0.27$ $h/b = 0.02$ at $x = 1.00$
WADC-Aeroproducts	12.00	3	Solid steel NACA 16-series symmetrical	Tapered (linear): $b = 19.55$ in. at $x = 0.27$; $b = 14.07$ in. at $x = 1.00$	$h/b = 0.06$ at $x = 0.27$ $h/b = 0.02$ at $x = 1.00$
NACA 10-(3)(049)-03	10.05	2	Solid duralumin NACA 16-series; $c_{l_d} = 0.30$ from root to tip	Rectangular (8-in. chord)	$h/b = 0.11$ at $x = 0.27$ $h/b = 0.025$ at $x = 1.00$

TESTS

Blade-twist data were obtained in the wind tunnel and at the static test stand in essentially the same manner. At each test point five readings were taken on the electronic counter. Blade-twist was then calculated for each reading and the results averaged. The electronic-counter readings were not averaged directly because it was desired to note the ability of the instrument to repeat data in terms of blade twist rather than a time interval in seconds. Since the optical deflectometer measured a change in blade angle from a reference operating condition to any operating condition, it was found necessary to correct the measured values of blade twist by a calculated value at the reference condition of operation. The reference condition of operation was chosen as the lowest rotational speed at which a constant number of revolutions per minute could be held.

WADC-Aeroproducts propeller.- In the wind-tunnel investigation of the WADC-Aeroproducts propeller, the primary objective was the determination of the 1-P vibratory characteristics of the propeller, and the tests were run at or near zero thrust. The zero-thrust condition for a given blade-angle setting was maintained by increasing the stream Mach number and the propeller rotational speed up to the maximum rotational speed (2,100 rpm). Blade twist was measured during the tests at the 0.75 radial station for $\beta_{0.75R} = 19.7°$ and $39.1°$ at forward Mach numbers up to 0.74.

Curtiss-Wright 109622 propeller.- The wind-tunnel tests of the Curtiss-Wright 109622 propeller, for which blade-twist data were obtained at the 0.75 radial station, were made at constant forward Mach numbers for $\beta_{0.75R} = 54.7°$ and $60.2°$. Since the primary purpose of the Curtiss-Wright propeller wind-tunnel tests was the determination of the aerodynamic characteristics of the propeller, the rotational speed was varied (at a constant stream Mach number) to obtain data from a lightly loaded to a heavily loaded condition. The maximum stream Mach number and rotational speed at which blade twist was measured were 0.96 and 2,080, rpm, respectively.

NACA 10-(3)(049)-03 propeller.- Blade twist was measured at the 0.70 radial station for $\beta_{0.75R} = 0°$, $4°$, $8°$, and $12°$ at zero advance for rotational speeds up to 1,800 rpm for the NACA 10-(3)(049)-03 propeller. This two-blade propeller has one solid blade and one blade in which tubes were embedded for measuring the surface pressures at several chordwise and spanwise stations. For this investigation the prism was

mounted on the solid blade of the propeller. Generally for the blade-angle settings where the rotational-speed range is limited, the limitation was caused by flutter or failure of the deflectometer equipment.

ACCURACY

Blade twist.- It was determined during the calibration test of the optical deflectometer that the instrument could measure the change in propeller-blade-angle setting with an accuracy equal to that with which the propeller blade could be set ($\pm0.05^\circ$). The calibration curve for the instrument is shown in figure 7.

During the propeller tests in the wind tunnel and at the static test stand, any one of the five readings taken at a given test point agreed with the average of the five readings within $\pm0.05^\circ$. Another indication of the accuracy of the instrument was its ability to repeat data for a complete test run. A repeat run made during the test of the WADC propeller indicated that an agreement of 0.10° existed between the two sets of data.

Based on the calibration tests and a study of the data obtained from the instrument, it is believed that the optical deflectometer measured changes in blade angle of an operating propeller within $\pm0.10^\circ$.

Propeller rotational speed and Mach number.- Propeller rotational speed was determined with an accuracy of $\pm1/4$ of a revolution per minute and the stream Mach number was known to ±0.01.

METHODS AND CALCULATIONS

Data Reduction

The test data obtained during the investigation of the NACA 10-(3)(049)-03 propeller were reduced to blade twist using the following equation (see ref. 6):

$$\Delta\beta = \frac{y}{z}\left[\sin\left(360 \times n_1 \times t_1\right) - \sin\left(360 \times n_0 \times t_0\right)\right]$$

During the wind-tunnel tests of the WADC-Aeroproducts and Curtiss-Wright propellers the deflectometer reference signal did not register on the photoelectric cell when the blade was in the bottom vertical position, as it did for the NACA 10-(3)(049)-03 propeller tests, therefore a correction c was employed in the equation used to reduce the measured parameters to blade twist. The following equation for blade twist was used:

$$\Delta\beta = \frac{y}{z}\left[\sin\left(360 \times n_1 \times t_1 - c\right) - \sin\left(360 \times n_0 \times t_0 - c\right)\right]$$

Values of $c = 3.0°$ and $20.5°$ were recorded for the WADC-Aeroproducts and Curtiss-Wright propellers, respectively.

Calculated values of blade twist (by the method given in the following section), based on centrifugal effects only, are tabulated for the following reference test conditions at the 0.75 radial station for the WADC-Aeroproducts and Curtiss-Wright propellers and at the 0.70 radial station for the NACA 10-(3)(049)-03 propeller:

Propeller	Rotational speed at reference condition, rpm	$\beta_{0.75R}$, deg	$\Delta\beta$, deg
WADC-Aeroproducts	600	19.7 39.1	0.28 .20
Curtiss-Wright	600	54.7 60.2	.08 .11
NACA 10-(3)(049)-03	500	0 4 8 12	.13 .12 .10 .09

Theoretical Blade-Twist Calculations

Values of blade twist at several test conditions were calculated for the WADC-Aeroproducts, Curtiss-Wright, and NACA 10-(3)(049)-03 propellers. In calculating the values of blade twist the method used was similar to that given in reference 1:

$$\Delta\beta = \frac{180}{\pi} \int_0^r \frac{M_a + M_c + M_p}{GJ_T{}'} \, dr$$

In this equation the blade twist at any radial station is a function of the aerodynamic twisting moment M_a, the tensile torsional moment M_c, the planipetal torsional moment M_p, the shear modulus of elasticity G, and the total torsional-stiffness constant $J_T{}'$. A complete description of the variables in the blade-twist equation is given in reference 1; briefly M_a can increase or decrease the blade angle depending on the chordwise location of the center of pressure relative to the flexural axis, M_c tends to increase the blade angle, and M_p decreases the blade angle (for positive blade-angle settings).

For the calculated values of blade twist in which the aerodynamic twisting moment was evaluated, lift coefficient, drag coefficient, and pitching-moment coefficient were obtained from references 7, 8, and 9. For some of the calculations it was necessary to extrapolate the data presented in these references for lower thickness ratios and higher angles of attack.

As noted in reference 2, thin propellers having high activity factors will exhibit an increase in torsional stiffness above the calculated torsional stiffness obtained from membrane analogy (ref. 10). The calculated values of blade twist presented in this report are based on a total torsional-stiffness constant $J_T{}'$ which considers this increase in torsional stiffness. For a thin symmetrical 16-series airfoil section:

$$J_T{}' = J'\left[1 + 0.0145\, \frac{E}{G}\left(\frac{b}{h}\right)^2 b^2 \left(\frac{d\beta}{dr}\right)^2\right]$$

where J' is the value of the torsional-stiffness constant based on membrane analogy and has the following value for a symmetrical NACA 16-series airfoil section $J' = 0.1793bh^3$ (ref. 2).

In calculating the blade twist for a given condition, it was necessary to perform on the average three iterations before convergence was assured to the extent that blade twist could be determined within $\pm0.03°$ of a final value. An iterative process is necessary because the

moments involved in the blade-twist equation are a function of blade
angle or the slope of the curve of blade angle plotted against propeller
radius.

RESULTS AND DISCUSSION

WADC-Aeroproducts propeller.- Measured values of blade twist are
presented in figure 8 as a function of propeller rotational speed for
$\beta_{0.75R} = 19.7^{\circ}$ and 39.1°. Rotational speed was chosen as a parameter
for plotting the data because blade twist was found to be primarily a
function of centrifugal force. A maximum value of 2.57° of blade twist
was measured at 2,100 rpm for the 19.7° blade angle. At the 39.1° blade
angle, the maximum measured value of blade twist was 1.71° at 2,075 rpm.
Examination of the effect of blade-angle variation on the centrifugal
twisting moments indicates that the larger value of blade twist measured
at the lower blade angle is to be expected. For positive blade-angle
settings, the planipetal twisting moment tends to decrease the propeller
blade angle, and, for a given rotational speed, its magnitude varies as
the $\sin 2\beta$. The tensile untwisting moment, which tends to increase
blade angle is not a function of blade angle but of the pitch distribu-
tion of the propeller, and remains constant for a given rotational speed
as the propeller blade angle varies. The summation of the two moments
at a given rotational speed will therefore give a larger net moment at
the lower blade-angle setting.

Calculated values of blade twist in which only centrifugal effects
were considered are also presented on figure 8 at both blade angles
$\left(\beta_{0.75R} = 19.7^{\circ} \text{ and } 39.1^{\circ}\right)$. The calculated and measured values of blade
twist for the 19.7° blade angle were found to be in excellent agreement
at 1,300 rpm and differed by 0.47° at 2,050 rpm. At the 39.1° blade
angle the calculated values were from 0.2° to 0.4° higher than the meas-
ured values. When the aerodynamic twisting moment was included in the
calculations it tended to decrease the total calculated values at
2,050 rpm for both blade angles by 0.10°. Since the WADC-Aeroproducts
propeller was operating at or near zero thrust throughout the inves-
tigation, the small contribution of the aerodynamic moment is not sur-
prising. The inclusion of the aerodynamic twisting moment brings the
agreement between measured and calculated values of blade twist at
2,050 rpm within 0.35° for both blade angles. This agreement is con-
sidered herein as fair.

Curtiss-Wright propeller.- Measured values of blade twist at the
0.75 radial station are presented in figure 9 for the Curtiss-Wright
propeller as a function of propeller rotational speed at several Mach

numbers for $\beta_{0.75R} = 54.7^\circ$ and 60.2°. Analysis of the measured data
indicates that for the 54.7° blade angle the values of blade twist are
practically independent of Mach number and rotational speed. For the
three Mach numbers presented in figure 9(a) (M = 0.89, 0.93, and 0.96)
the magnitude of blade twist varies from about 0.6° to 0.8°. At the
60.2° blade-angle setting (fig. 9(b)) the measured values of blade
twist are within a band from 0.4° to 0.9° for the three Mach numbers
(M = 0.89, 0.93, and 0.96) shown for all values of rotational speed.
There does not appear to be any consistent variation of $\Delta\beta$ with
rotational speed as forward Mach number is varied. If the faired data
for the three Mach numbers were superimposed upon each other for rota-
tional speeds up to 1,700 rpm, the curves would agree with each other
within the accuracy of the measurements. An explanation of why this
agreement is reasonable will be given in the following discussion of
the calculated results.

Calculated values of blade twist in which only centrifugal effects
were considered are also presented in figure 9. The agreement between
measured and calculated results is excellent at $\beta_{0.75R} = 54.7^\circ$
(fig. 9(a)) while at $\beta_{0.75R} = 60.2^\circ$ (fig. 9(b)) discrepancies of
about 0.20° occur between the calculated and measured data. The results
indicate that the aerodynamic contribution to blade twist for this pro-
peller must be very small. This is indicated by theory and results of
airfoil tests in which it can be shown that the center of pressure of a
thin symmetrical airfoil in supersonic flow moves from the subsonic
quarter-chord location to near the midchord location. For an NACA
16-series airfoil section in supersonic flow, therefore, the center of
pressure would be very close to the center-of-gravity location (or
flexural axis) and very little aerodynamic twisting moment would be
expected. Noting the high tip Mach numbers and forward Mach numbers
of the data presented in figure 9, it is concluded that the aerodynamic
contribution to blade twist for the Curtiss-Wright propeller should be
small.

NACA 10-(3)(049)-03 propeller.- Actually the NACA 10-(3)(049)-03
propeller is not in the supersonic-type propeller category based on pres-
ent section-thickness-ratio criteria for supersonic propellers. The
radial thickness-ratio distribution of the NACA propeller would probably
put it in a category between the subsonic and supersonic propeller. How-
ever, for purposes of analysis and lack of data at zero advance for the
WADC-Aeroproducts or Curtiss-Wright propeller, the NACA 10-(3)(049)-03
propeller has been included in the discussion of blade twist of super-
sonic propellers.

Measured values of the blade twist at the 0.70 radial station for
the NACA 10-(3)(049)-03 propeller are presented in figure 10 as a func-
tion of propeller rotational speed for $\beta_{0.75R} = 0^\circ$, 4°, 8°, and 12° at

zero advance. The maximum measured value of blade twist for this propeller was $1.96°$ at $\beta_{0.75R} = 4°$ and 1,800 rpm. For the other blade angles ($0°$, $8°$, and $12°$), data were not obtained at as high a rotational speed and the maximum measured values of blade twist were considerably lower than at $\beta_{0.75R} = 4°$. For rotational speeds from 500 to 1,000 rpm, the measured values of blade twist are about the same for the four blade angles at a given rotational speed. The fact that blade twist is independent of blade angle in this speed range indicates that the aerodynamic twisting moment is probably increasing as blade angle increases and offsets the planipetal twisting moment tending to decrease the blade twist. This is substantiated by the decrease in the calculated values of blade twist, based on centrifugal effects (aerodynamic effects neglected), at a given rotational speed as blade angle is increased (fig. 10). In general the agreement between measured and calculated values (based on centrifugal effects) is excellent below 1,000 rpm. Above 1,000 rpm the two sets of data diverge. When the aerodynamic twisting moment was evaluated for the highest rotational speed at each blade angle the following agreement between measured and calculated data was obtained:

a. For $\beta_{0.75R} = 0°$ and 1,350 rpm, the aerodynamic twisting moment decreased the calculated blade twist (based on centrifugal effects) by $0.18°$ and gave perfect agreement between the measured and total calculated values. This decrease in blade twist due to aerodynamic effects is reasonable because a large portion of the blade is operating at negative angles of attack.

b. At $\beta_{0.75R} = 4°$ and 1,800 rpm, the aerodynamic twisting moment increased the calculated blade twist (based on centrifugal effects) by $0.4°$ and the agreement between the measured and total calculated values was within $0.15°$.

c. At $\beta_{0.75R} = 8°$ and $12°$ at rotational speeds of 1,150 and 1,100 rpm, respectively, the aerodynamic twisting moment increased the calculated values of blade twist (based on centrifugal effects) to total values about $0.20°$ above the measured values. It should be noted that for these two blade-angle settings it was necessary to extrapolate the two-dimensional airfoil data to higher angles of attack for the inboard blade stations.

An overall analysis of the measured and total calculated values of blade twist (centrifugal and aerodynamic effects evaluated) indicates excellent agreement.

The general conclusions to be drawn from the data presented at zero advance are that blade twist can be calculated (based on centrifugal

effects) accurately for lightly loaded conditions of operation; however, there are indications that the aerodynamic twisting moment should be evaluated when the propeller loading increases due to either an increase in rotational speed or blade-angle setting.

Analysis of the measured and calculated results for the three propellers tested.- An analysis of the measured and calculated values of total blade twist for the three propellers tested indicates excellent agreement for the NACA 10-(3)(049)-03 propeller, good agreement for the Curtiss-Wright propeller, and good to fair agreement for the WADC-Aeroproducts propeller (depending on the rotational speed under consideration). In analyzing the calculated results, the effect of the increased torsional stiffness for the three propellers was noted. The radial variation of the increased torsional-stiffness factor J_T'/J' for the three propellers is given in figure 11. From this figure it may be noted that the WADC-Aeroproducts propeller has the greatest value of the additional torsional-stiffness factor for almost all blade radial stations. The Curtiss-Wright propeller also exhibits a high value of the increased torsional stiffness factor but not as great as the WADC-Aeroproducts propeller. The NACA 10-(3)(049)-03 propeller shows the smallest value of the additional torsional-stiffness factor ($J_T'/J' \approx 1.10$).

In the derivation of the total torsional-stiffness constant J_T' (ref. 2), the assumption was made that to the first approximation plane cross sections remain plane under torsional deformation. It is possible therefore that for large values of blade torsional deformation the values of the total torsional-stiffness constant used to calculate blade twist may be subject to second-order effects. It would be expected then that the calculations of blade torsional deflection for the WADC-Aeroproducts propeller with its large torsional deflections and large torsional-stiffness factor would be influenced to a greater degree by any second-order effects on the evaluation of the total torsional-stiffness constant than would the calculations for the Curtiss-Wright or the NACA 10-(3)(049)-03 propeller.

Comparison of blade twist for the Curtiss-Wright propeller and the WADC-Aeroproducts propeller.- A direct comparison of the measured values of blade twist for the Curtiss-Wright propeller and the WADC-Aeroproducts propeller is not possible since data were not obtained under comparable conditions (β, rotational speed, and forward velocity). It is evident, however, from the data already discussed that the WADC-Aeroproducts propeller is twisting more than the Curtiss-Wright propeller. In order to ascertain the relative values of blade twist for the two propellers on a comparable basis, blade twist has been calculated (based on centrifugal effects) along the blade radius for $\beta_{0.75R} = 50^\circ$ at 2,100 rpm (fig. 12).

A value of $\Delta\beta_{0.75R} = 2.49^{\circ}$ was calculated for the WADC-Aeroproducts propeller and $\Delta\beta_{0.75R} = 0.79^{\circ}$ for the Curtiss-Wright propeller. In an effort to determine the contributing factors causing the difference in blade twist for the two propellers, the components entering into the calculations have been isolated and are presented in figure 12. Isolation of the components indicates that the value of the torsional-stiffness constant J_T' for the WADC-Aeroproducts propeller is 4.94 times greater than for the Curtiss-Wright propeller at $x = 0.30$, and 2.25 times greater at $x = 0.70$. The net centrifugal moment $(M_C - M_P)$, however, for the WADC-Aeroproducts propeller is 6.43 times greater than the Curtiss-Wright propeller at $x = 0.30$ and 17.50 times greater at $x = 0.70$. Inspection of the radial variation of J_T' and $M_C - M_P$ for both propellers indicates that $M_C - M_P$ is proportionately higher all along the blade radius for the WADC-Aeroproducts propeller than the corresponding J_T'. Therefore, since both propellers are made of steel (G is the same) it would be expected that the WADC-Aeroproducts propeller would twist more than the Curtiss-Wright propeller.

Radial distribution of blade twist.- Since the measured data presented in this report for the various propellers tested are at one radial station only, an insight as to the radial distribution of blade twist will have to be obtained from calculated values of blade twist. In figure 13 the calculated radial distribution of blade twist for the WADC-Aeroproducts propeller at several values of rotational speed at $\beta_{0.75R} = 19.7^{\circ}$ is presented. The calculated curves shown do not include aerodynamic effects, but as has been shown previously the aerodynamic contribution to blade twist for this propeller, operating at zero thrust, was small. A value of 3.86° of blade twist was calculated at the propeller tip compared with 2.92° at the 0.75 radial station for 2,050 rpm. For the other rotational speeds shown in the figure the blade twist at the tip was also about 35 percent greater than that at the 0.75 radial station.

Effect of increased torsional stiffness.- To illustrate the importance of including the increased torsional stiffness of thin propellers in the calculation of blade twist, a calculation has been made for the WADC-Aeroproducts propeller operating at 2,050 rpm and $\beta_{0.75R} = 19.7^{\circ}$ in which the increased torsional stiffness has been neglected. The results of this calculation are presented in figure 13 for comparison with the previously discussed radial values of blade twist in which the increased torsional stiffness was considered. At the 0.75 radial station the calculated value of blade twist neglecting the increased torsional stiffness (based on J') is 6.10°. When this value is compared with the calculated value of 2.92° $\left(\text{also at 2,050 rpm and } \beta_{0.75R} = 19.7^{\circ}\right)$ but in

which the increased torsional stiffness has been considered (based on J_T'), it becomes readily apparent how important it is that increased stiffness of thin propellers be considered. Had the increased torsional stiffness not been included, a value of blade twist 109 percent too high would have been calculated. The present blade-twist measurements indicate that thin propellers do experience an increased torsional stiffness greater than the torsional stiffness indicated from the membrane analogy.

Variation of blade twist with blade angle at a constant rotational speed.- The variation of blade twist with blade angle for a constant rotational speed is interesting because the overall picture of blade twist under various operating conditions is obtained for a constant-speed propeller. Calculations of blade twist (based on centrifugal effects) at $x = 0.75$ for the WADC-Aeroproducts propeller at various blade angles and at a rotational speed of 2,050 rpm are presented in figure 14. The majority of the blade angles selected for the calculations are the same as those for which the propeller vibratory characteristics were determined during the wind-tunnel tests. The $\beta_{0.75R} = -15°$ blade angle represents the propeller operating as a brake. The minimum value of blade twist is 2.14° and occurs at $\beta_{0.75R} = 40°$. As noted in the discussion of the measured results for the WADC-Aeroproducts propeller, the tensile untwisting moment which tends to increase the propeller blade angle remains constant for a given rotational speed as the blade angle is varied, whereas the planipetal twisting moment which tends to decrease the propeller blade angle varies as the $\sin 2\beta$. It is therefore evident that the planipetal twisting moments along the blade radius have attained a maximum resultant value at $\beta_{0.75R} = 40°$ since the algebraic sum of the two centrifugal moments produces the minimum value of blade twist. For blade angles higher or lower than 40°, the value of blade twist increases. The maximum value of blade twist for the calculated data presented in figure 14 occurs at $\beta_{0.75R} = -15°$ and has a magnitude of 6.99°.

Examination of the general magnitude of blade twist at low positive blade angles (fig. 14) indicates that blade twist will have an adverse effect on the stall-flutter characteristics of the propeller. For instance, if a flutter speed for a given propeller has been estimated on the basis of its static blade-angle setting (blade torsional deformation under operating conditions neglected), it may be found when the propeller is actually tested that the rotational speed at flutter may be considerably lower than was estimated if the propeller blade has twisted to a higher angle than the static value. It is conceivable that, for a very thin propeller, blade twist may be of a sufficient magnitude to prevent flutter-free operation for any blade-angle setting

thus resulting in what is known as a closed flutter boundary at high rotational speeds.

Effect of blade twist on the aerodynamic characteristics of a propeller.- The effect of blade twist on the aerodynamic characteristics of a propeller has been calculated for one operating condition. In calculating the effect of blade twist it was assumed in one case that the propeller was rigid in torsion (static pitch distribution not altered by propeller operation) and each blade section operated at an angle of attack for maximum L/D at the design condition of operation. In the second case it was assumed that the propeller was not rigid in torsion and at the design condition of operation each section operated at an angle of attack greater than the angle for maximum L/D by an amount equal to the blade twist at the section. The design condition of operation assumed for both calculations was $M = 0.95$, $J = 2.20$, rotational speed, 2,100 rpm, and altitude, 40,000 feet. The geometry of the propeller was identical to the WADC-Aeroproducts propeller for both cases except that it had a static pitch distribution of

$$\beta_x = \phi_{o_x} + \alpha(L/D)_{max_x}$$

It should be noted that induced effects have not been included in the calculations. For the nonrigid propeller, a radial blade twist equal to that calculated for the WADC-Aeroproducts propeller at 2,100 rpm and $\beta_{0.75R} = 43.07°$ (based on centrifugal effects) was assumed at the operating condition. The results of the calculations are given in the following table:

Propeller	Efficiency	Thrust coefficient, C_T	Power coefficient, C_P
Rigid	0.777	0.0924	0.2618
Nonrigid	.751	.1375	.4030

Although the efficiency is only decreased by 2.6 percent for the nonrigid propeller, the thrust and power coefficients are changed by as much as 50 percent. A plot of the resulting thrust-coefficient and power-coefficient loadings is shown in figure 15 together with the calculated variation of blade twist. It should be pointed out, however, that for constant-speed propeller operation the large calculated changes in thrust and power coefficients would not occur since the blade angle

would be reduced slightly to maintain a constant power absorption. A loss in efficiency would still occur since the majority of the blade sections will operate at angles of attack greater or less than the angle for maximum L/D.

CONCLUSIONS

Measurement and calculation of blade-torsional deflection for the supersonic-type propellers investigated led to the following conclusions:

1. Blade-torsional deflection of supersonic-type propellers can be appreciable. A maximum value of blade-torsional deflection of 2.57° was measured at the 0.75 radial station for the WADC-Aeroproducts propeller for $\beta_{0.75R} = 19.7^\circ$ at 2,100 rpm.

2. In general the agreement between measured and calculated values of blade-torsional deflection was good; however, for the WADC-Aeroproducts propeller a discrepancy of 0.35° exists at the higher rotational speeds.

3. The aerodynamic twisting moment at supersonic blade section speeds for the Curtiss-Wright propeller was negligible as is indicated by theory.

4. Calculations of the aerodynamic twisting moment for the NACA 10-(3)(049)-03 propeller, which was operated at zero advance and subsonic tip Mach numbers, indicate that the aerodynamic contribution to blade twist can be appreciable.

5. Thin propeller blades experience an increased torsional stiffness greater than the torsional stiffness indicated by membrane analogy.

6. Blade twist calculations for the WADC-Aeroproducts propeller at a constant rotational speed and considering centrifugal effects only indicate that blade twist for an off-design condition of operation, for instance, the propeller operating as a brake, can be several times the value at the design condition of operation.

Langley Aeronautical Laboratory,
    National Advisory Committee for Aeronautics,
        Langley Field, Va., August 31, 1953.

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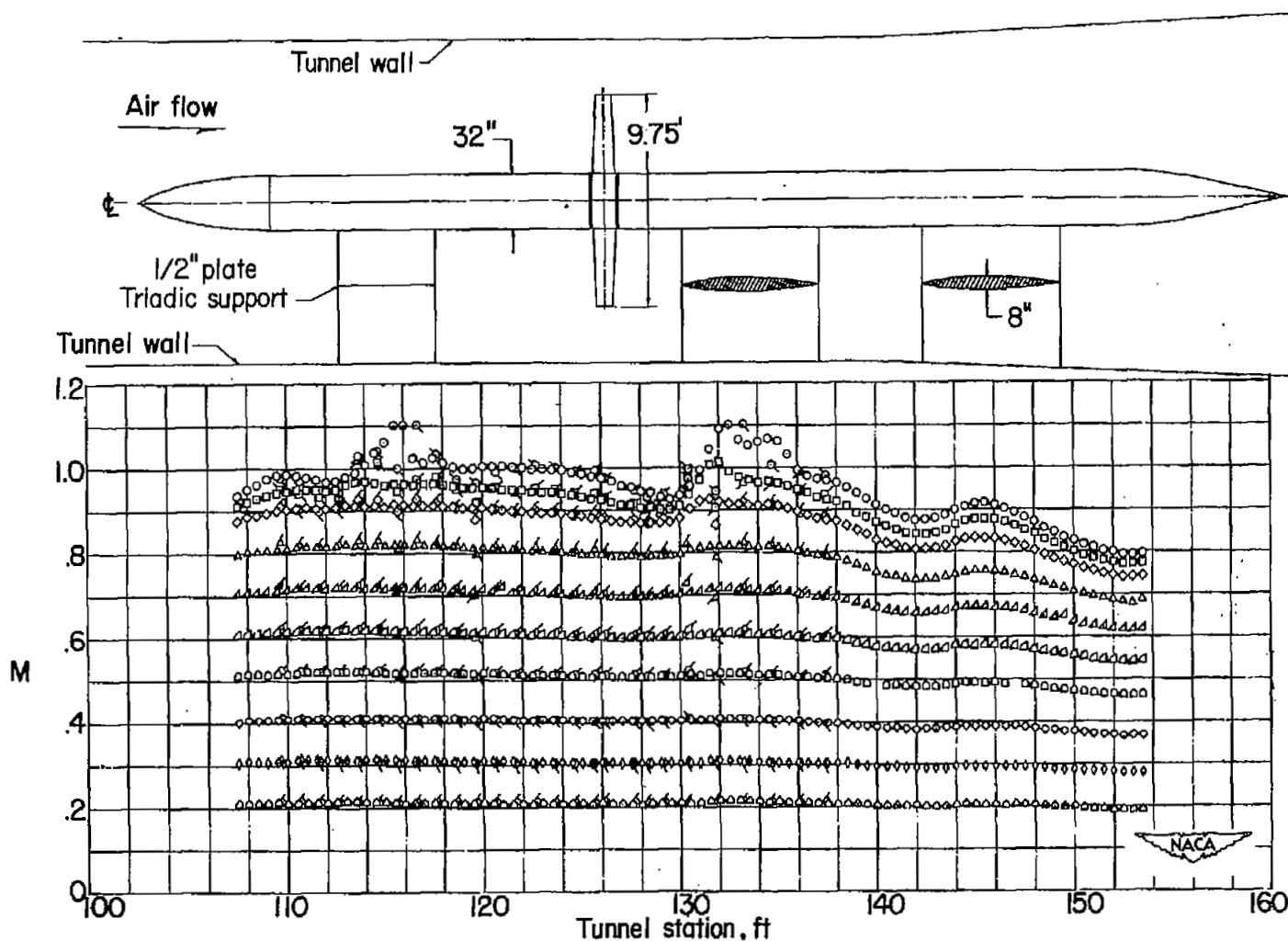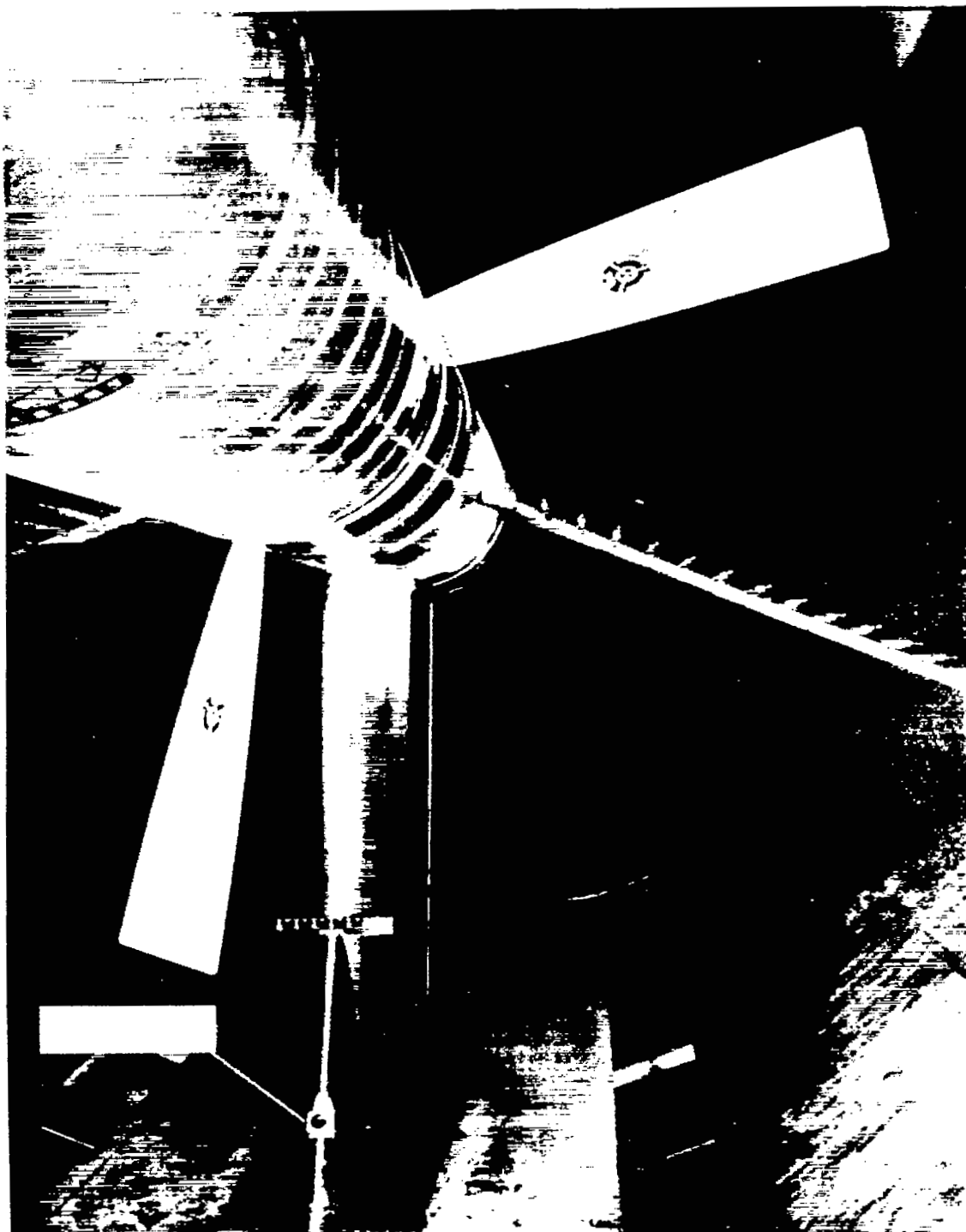   Book Co., Inc., 1934, p. 239.

Figure 1.- Sketch of propeller dynamometer and Mach number distributions
in the Langley 16-foot transonic tunnel with dynamometer but without
propeller installed. Flagged symbols indicate dynamometer body measure-
ments whereas symbols without flags represent tunnel-wall measurements.

L-75372.1

Figure 2.- Downstream view of dynamometer installed in the Langley 16-foot
transonic tunnel test section.

L-71314

Figure 3.- NACA 10-(3)(049)-03 propeller mounted on one unit of the 6000-horsepower propeller dynamometer at the Langley propeller static test stand.

Leading edge of dynamometer
support strut

Sheet-metal cover

Shock mount

Light source

Shield around light

Focusing lens

Shield to keep out stray light

Glass window

Prism glued to face of
photoelectric cell

Photoelectric cell

Cooling air supply

11"

24"

NACA
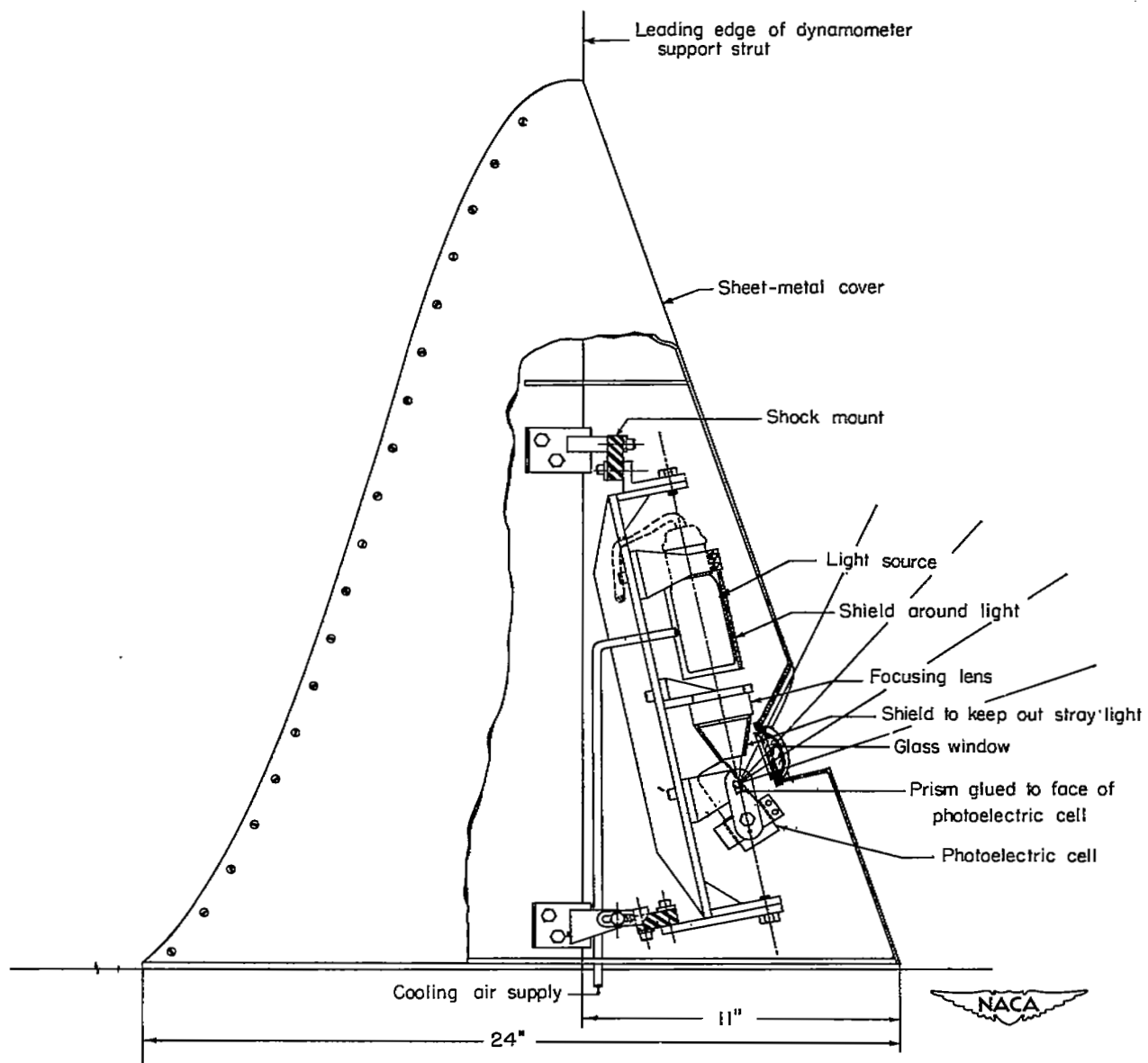
Figure 4.- Detail of deflectometer apparatus at base of dynamometer strut.

Air flow

Reference
prism

y

z

Blade prism
component (see
fig. 4)

A

A

Tank liner

Tunnel
wall

Blade
prism

c

Reference-prism
light source

Concentrated
light beam

Photoelectric
cell

NACA

Section A-A
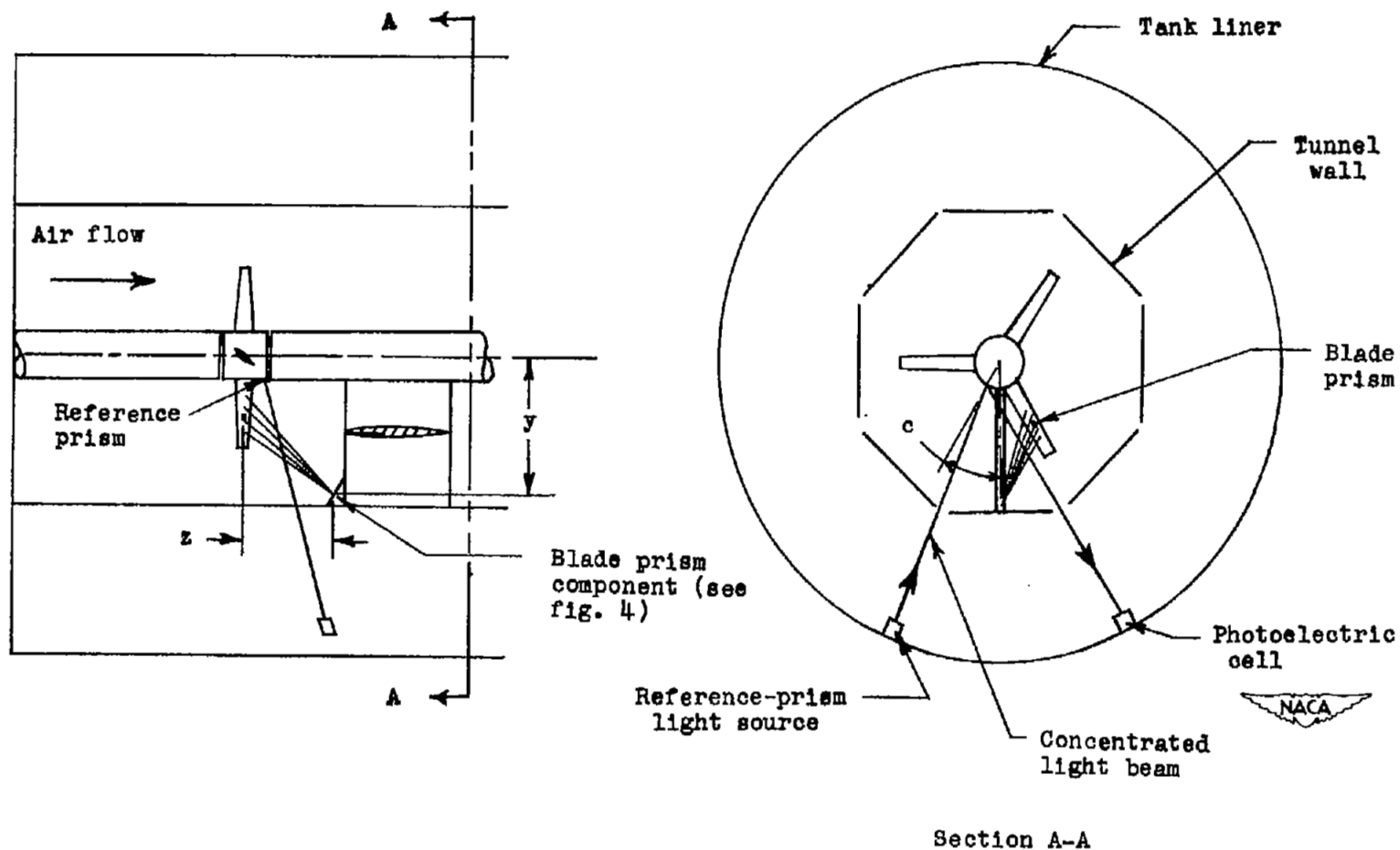
Figure 5.- Schematic diagram showing the location of the deflectometer
components in the Langley 16-foot transonic tunnel.
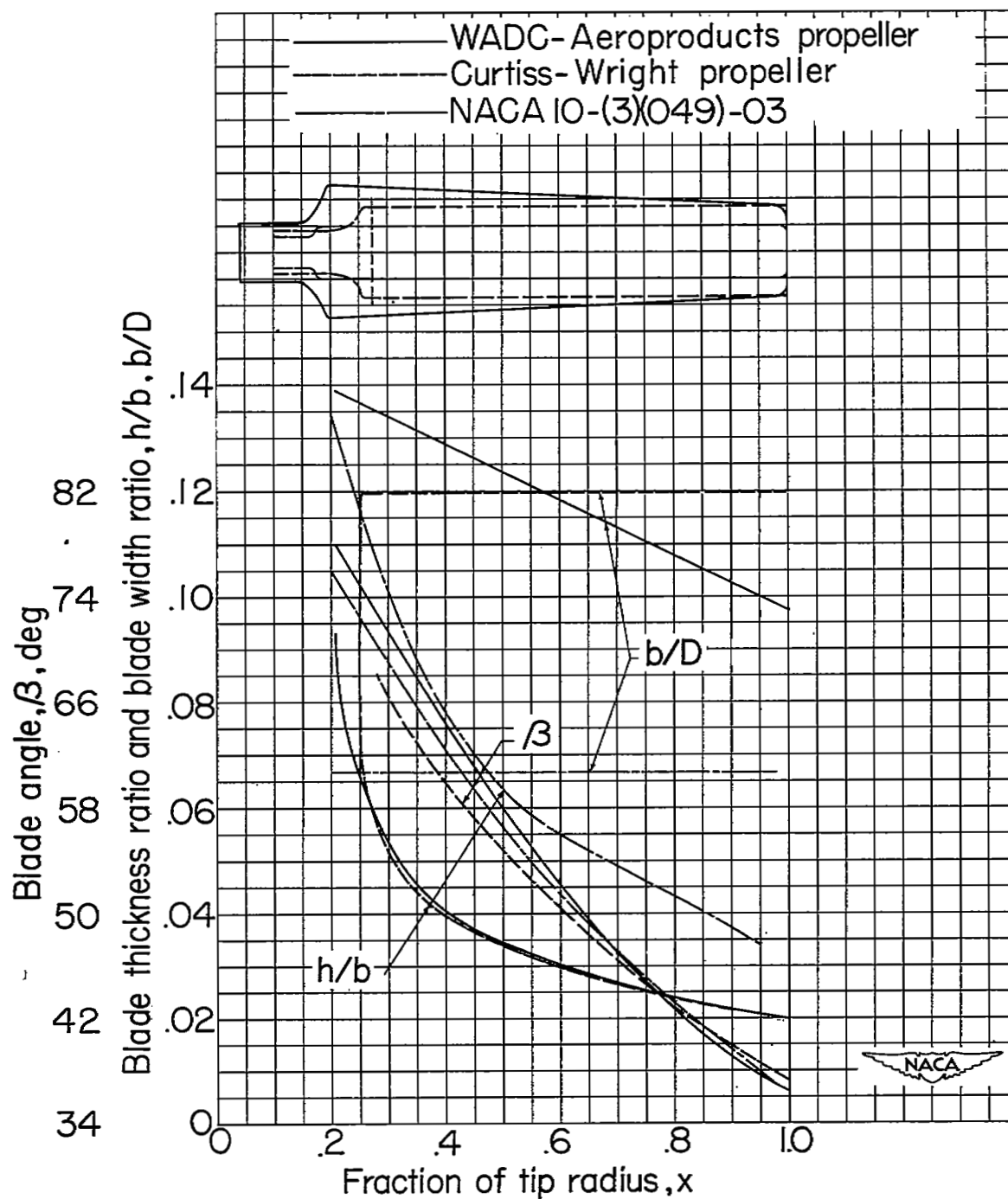
Figure 6.- Blade-form curves for propellers tested.
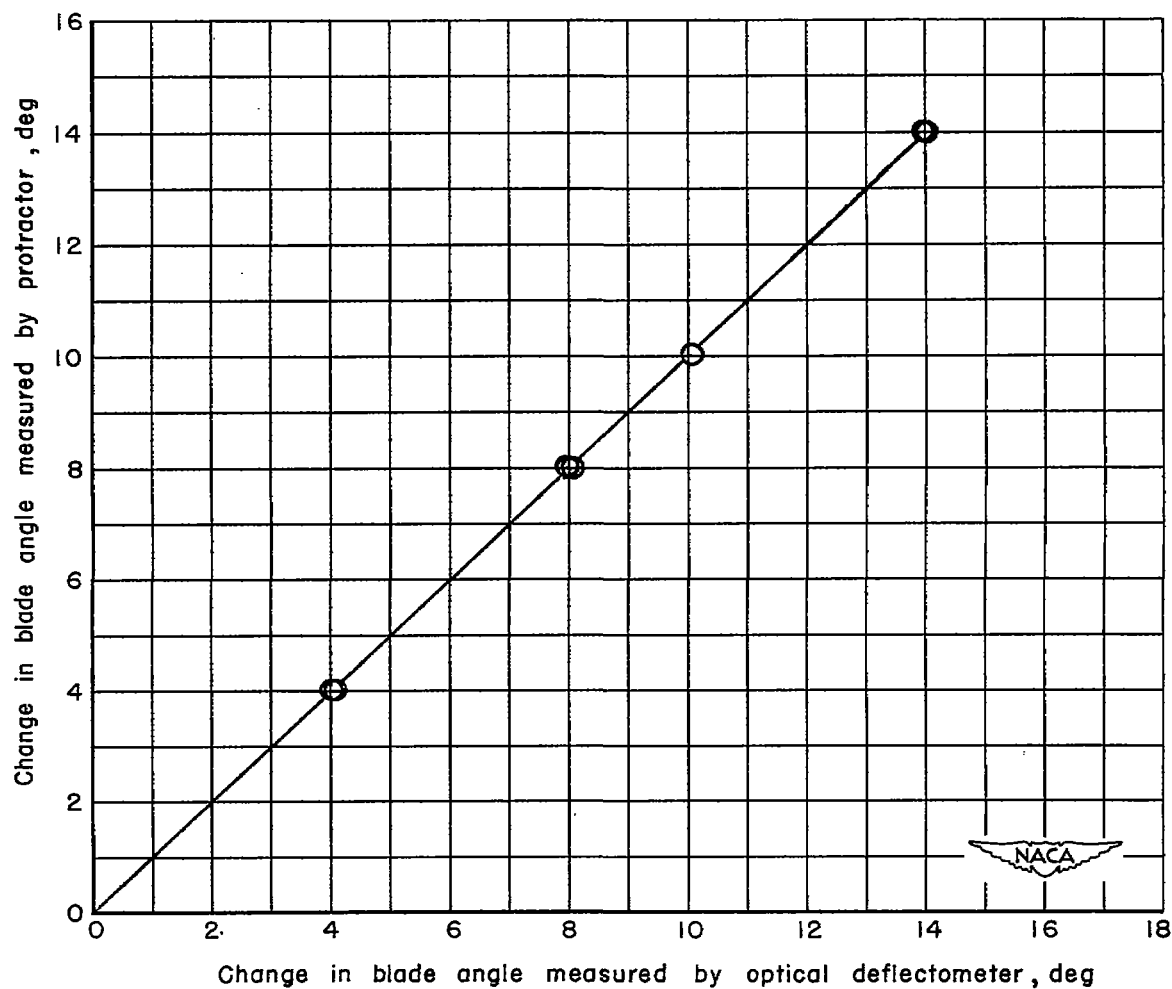
Figure 7.- Calibration curve for the optical deflectometer.
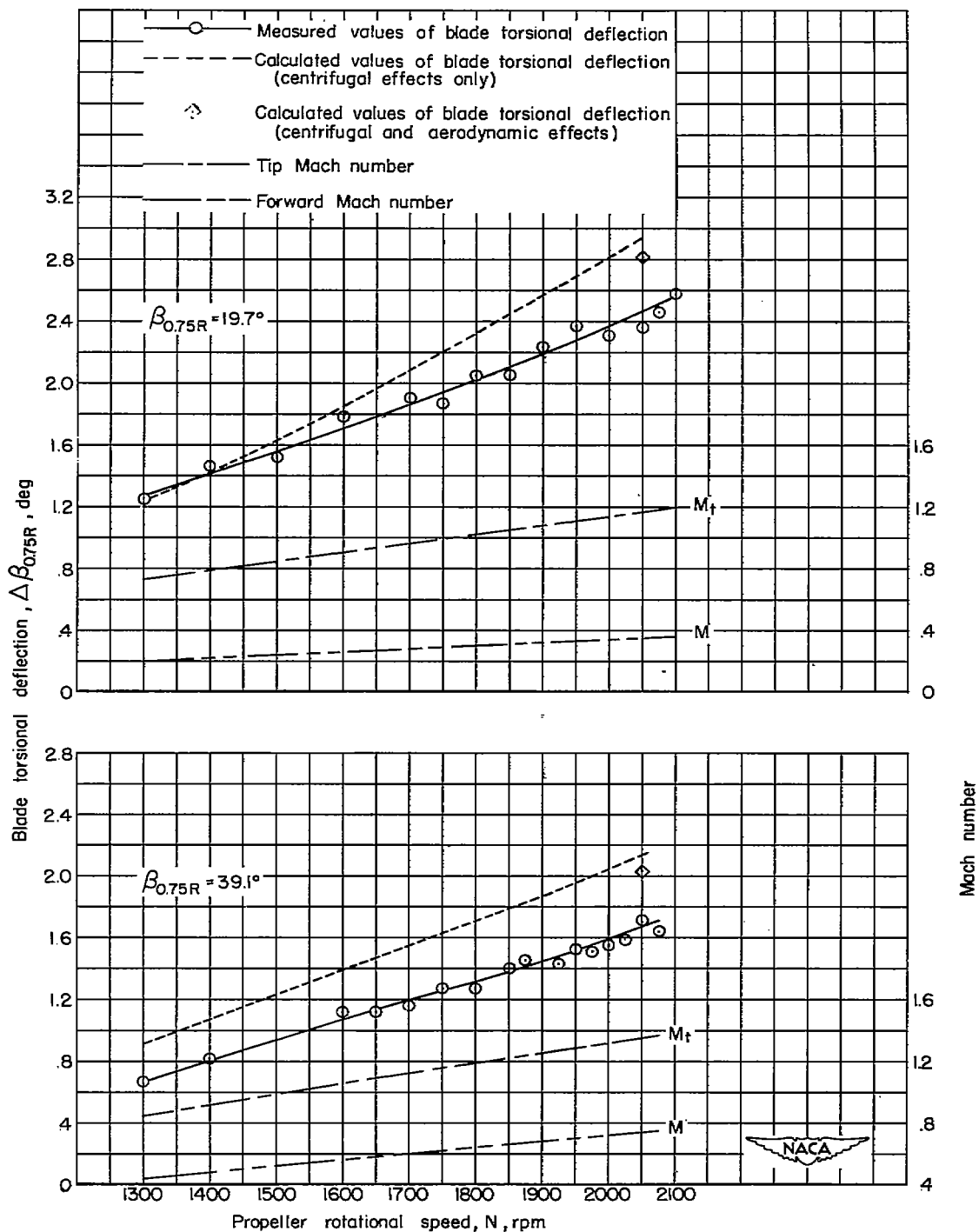
Figure 8.- Variation of measured and calculated values of blade torsional
deflection with propeller rotational speed for the WADC-Aeroproducts
propeller.
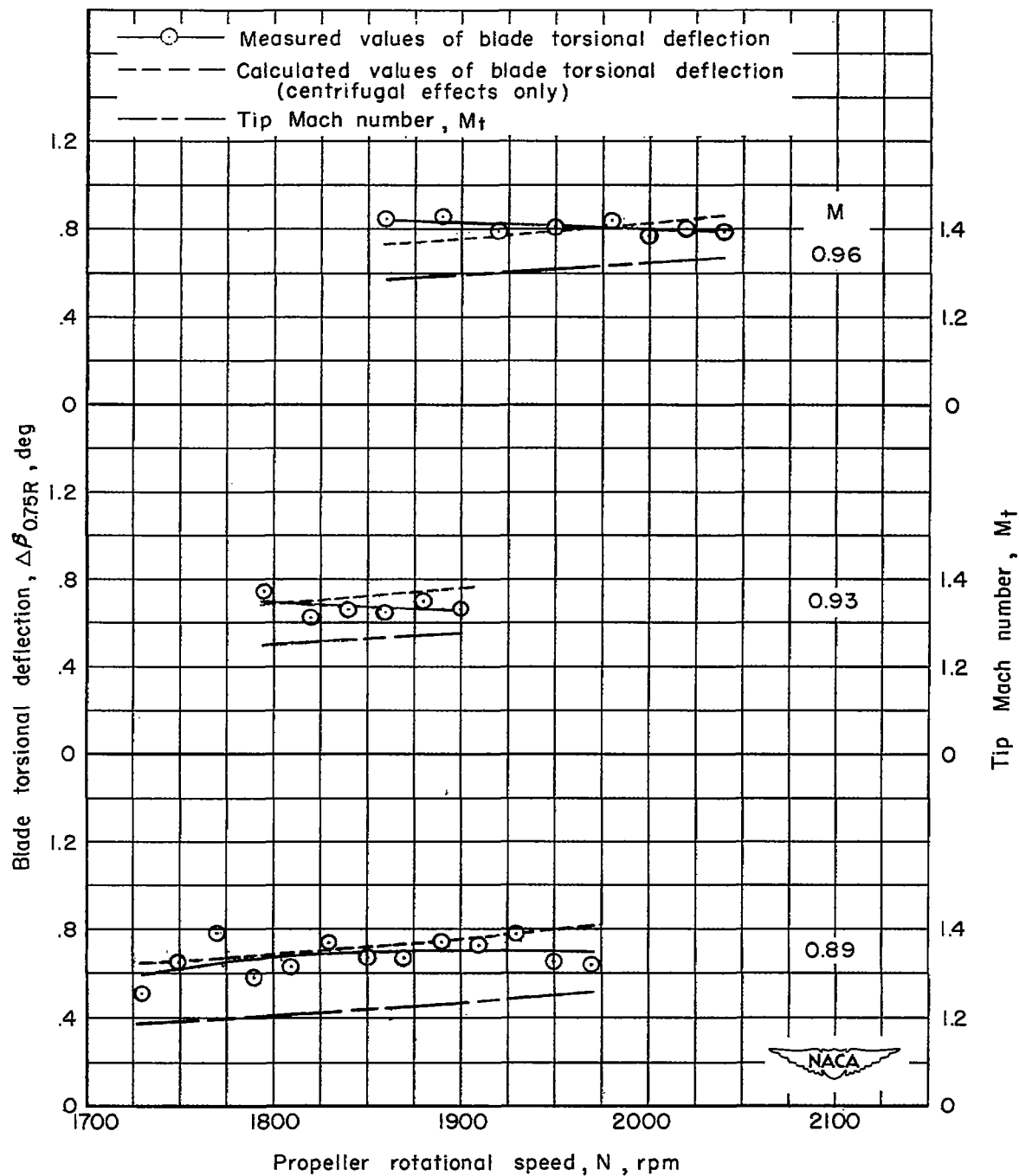
(a) $\beta_{0.75R} = 54.7°$.

Figure 9.- Variation of measured and calculated blade torsional deflection
for the Curtiss-Wright 109622 propeller.
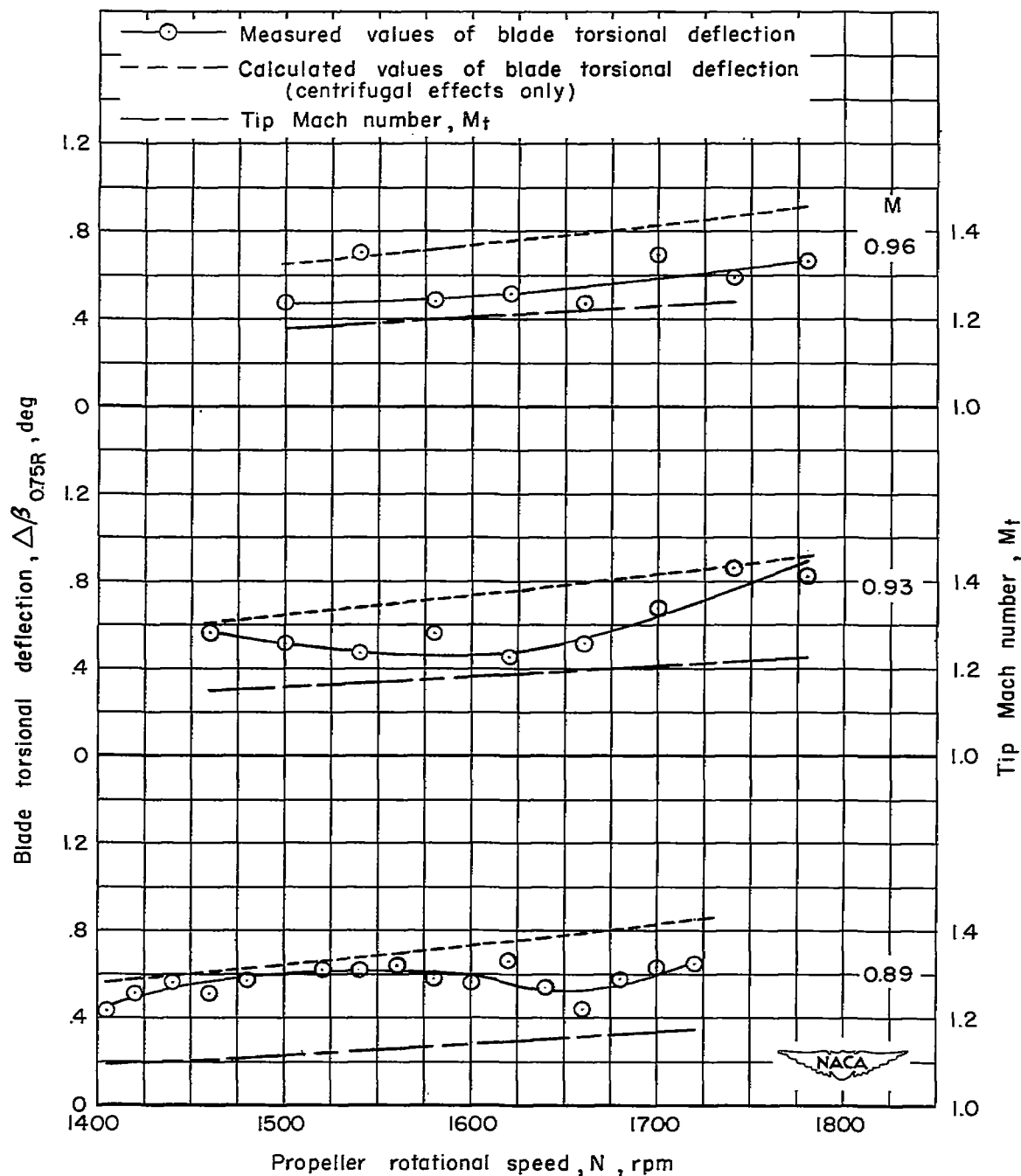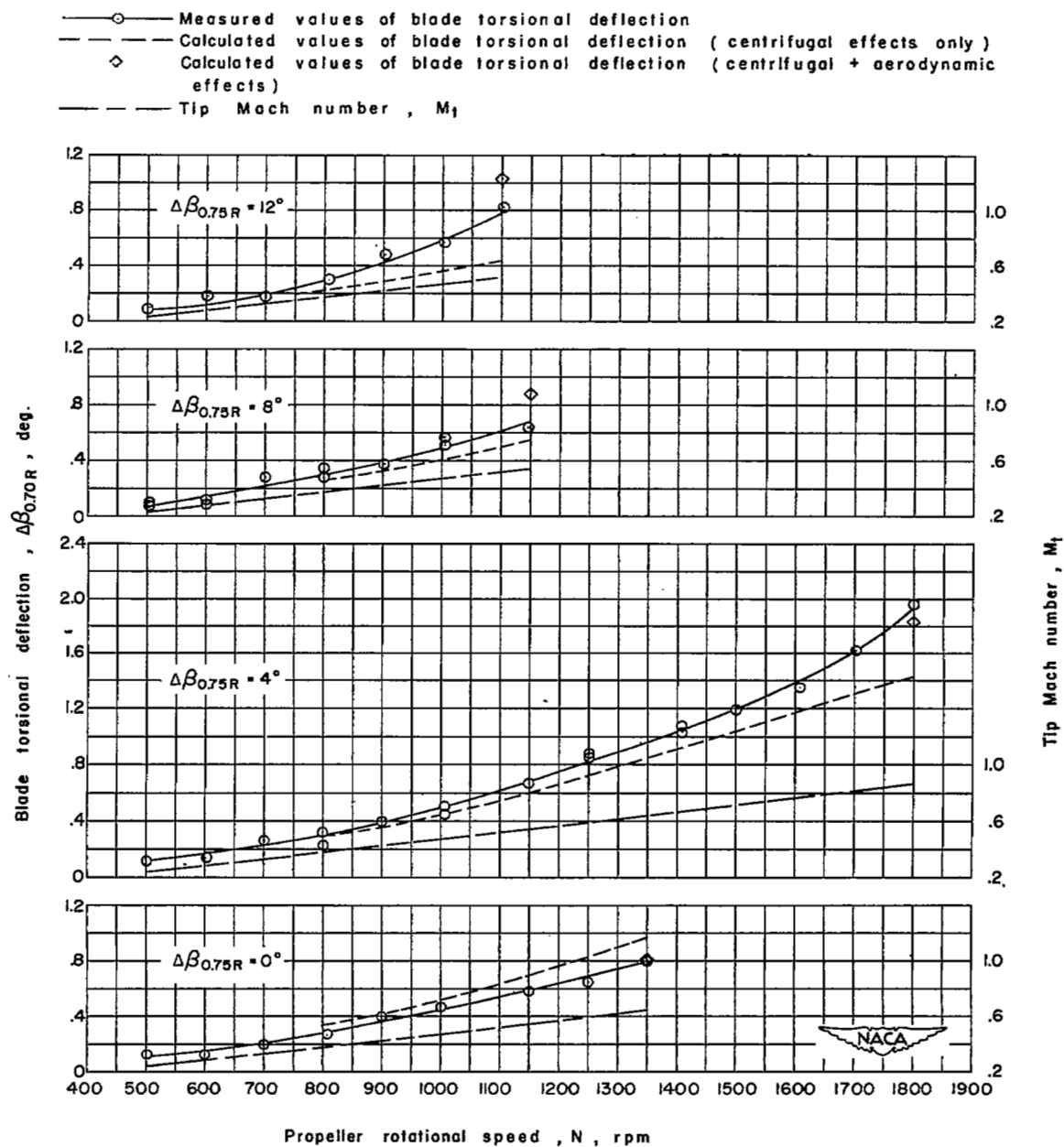
(b) $\beta_{0.75R} = 60.2°$.

Figure 9.- Concluded.

Figure 10.- Variation of blade torsional deflection with rpm for the
NACA 10-(3)(049)-03 propeller at zero advance.

$$\frac{J_{T'}}{J'} = \left[1 + \frac{0.0145}{G} E \left(\frac{b}{h}\right)^{2} b^{2} \left(\frac{d\beta}{dr}\right)^{2} \right]$$
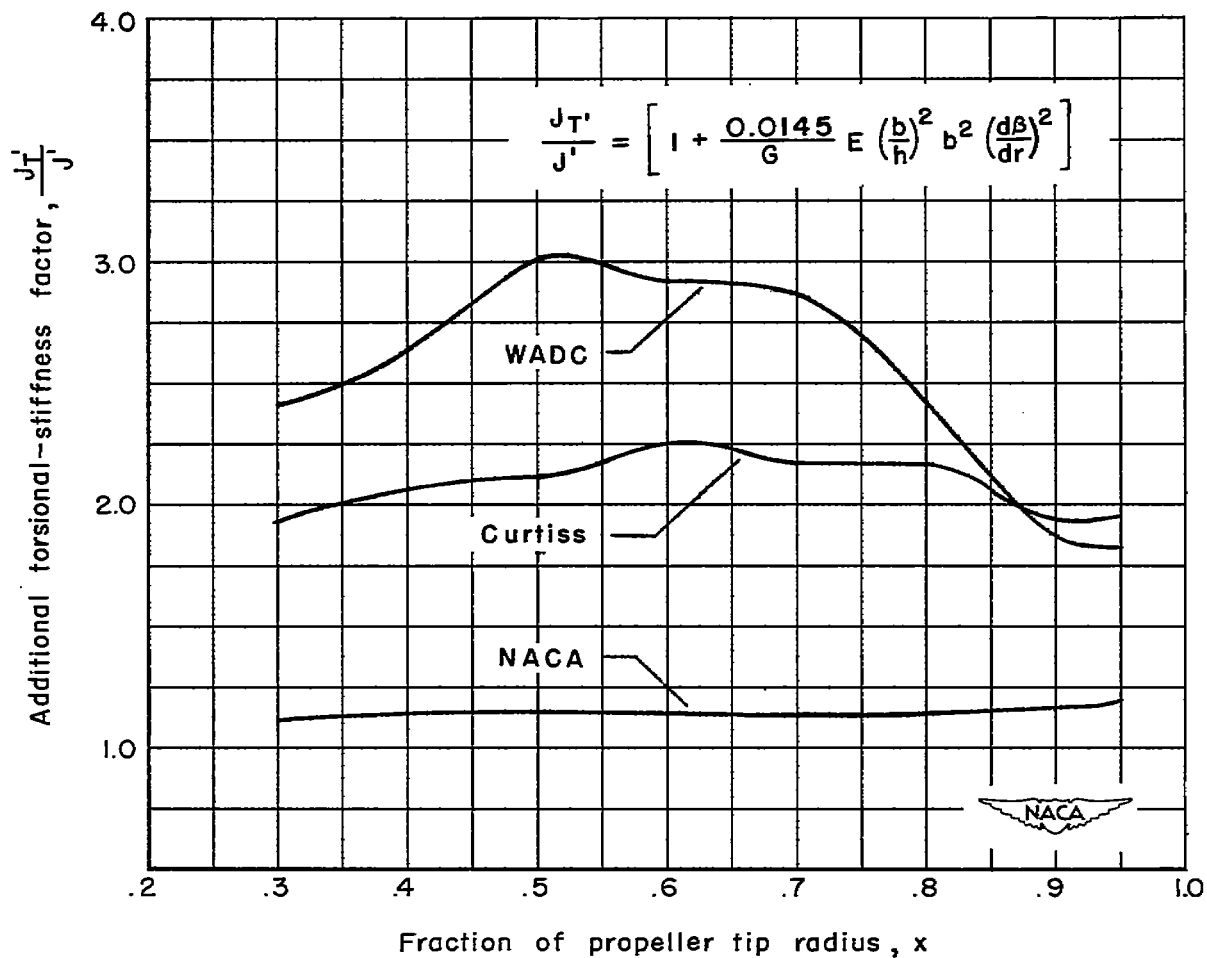
Figure 11.- Variation of the additional torsional-stiffness factor
   calculated for the WADC-Aeroproducts, Curtiss-Wright 109622, and
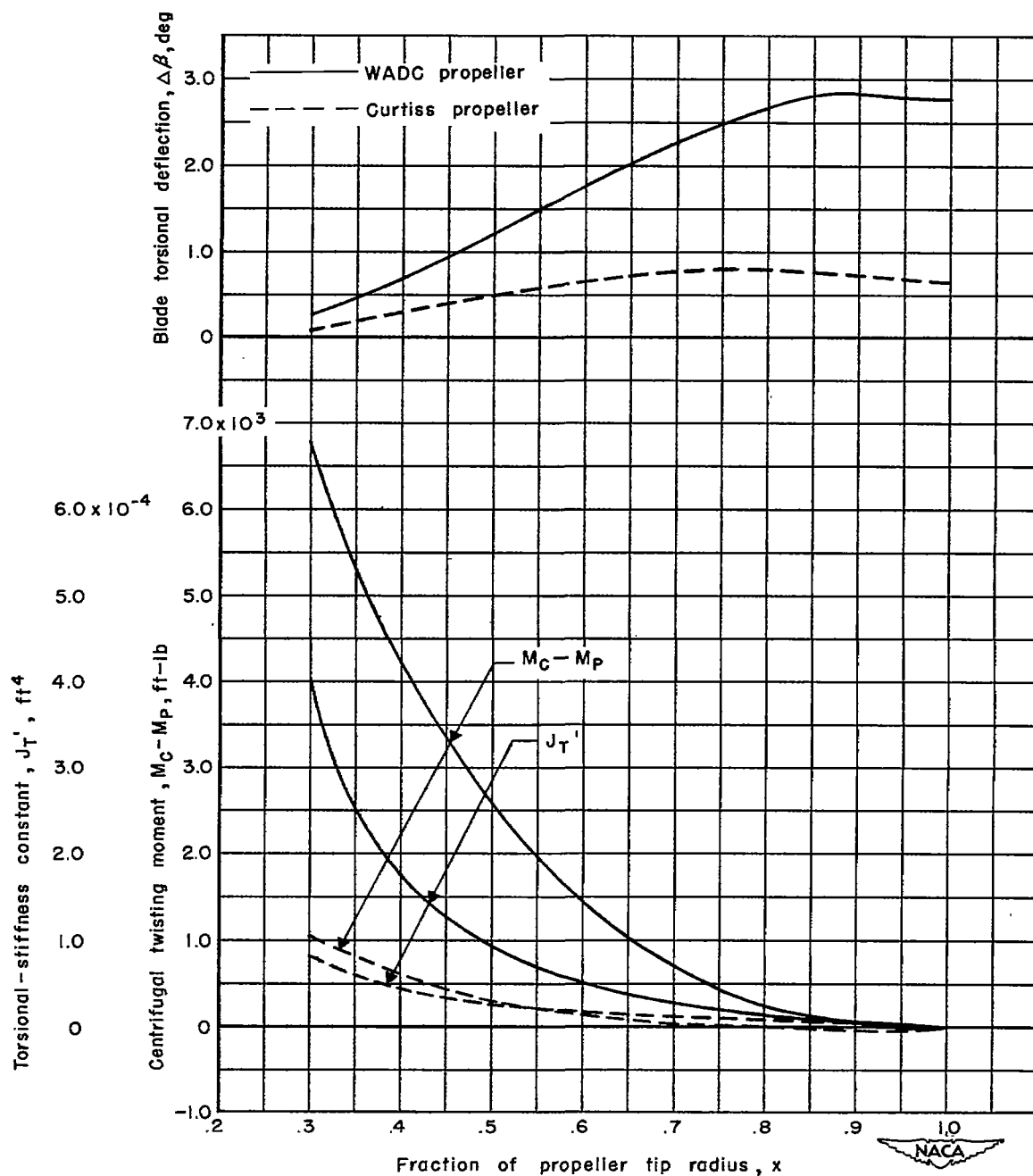   the NACA 10-(3)(049)-03 propellers.

Figure 12.- Variation of calculated blade torsional deflection based on centrifugal effects, M_t - M_P, and J_T' for the WADC-Aeroproducts and Curtiss-Wright 109622 propellers at $\beta_{0.75R}$ = 50° and 2,100 rpm.
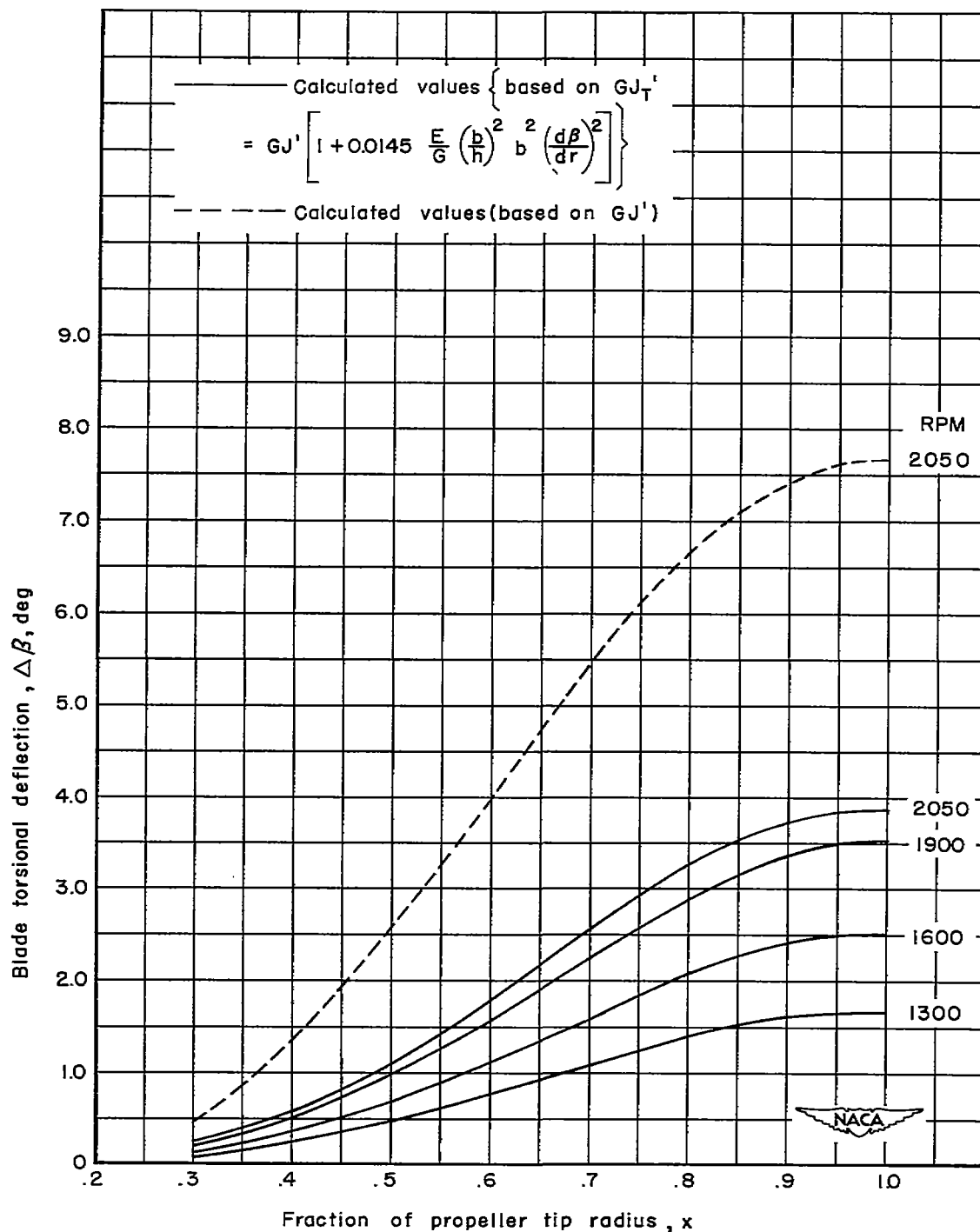
Figure 13.- Calculated radial variation of blade torsional deflection and effect of increased torsional stiffness for the WADC-Aeroproducts propeller. $\beta_{0.75R} = 19.7^{\circ}$.
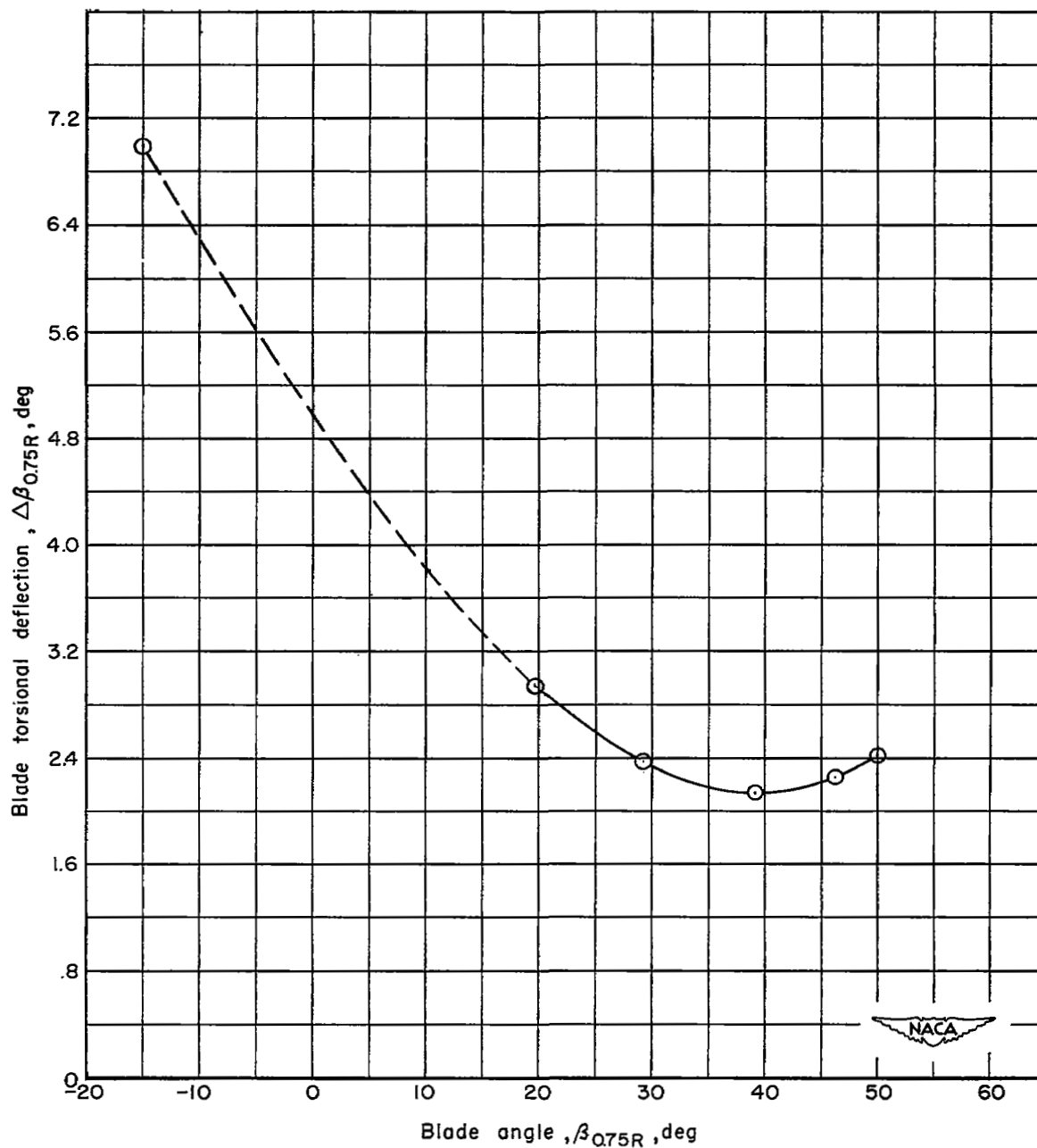
Figure 14.- Calculated variation of blade torsional deflection based on centrifugal effects with blade angle for WADC-Aeroproducts propeller at 2,050 rpm.
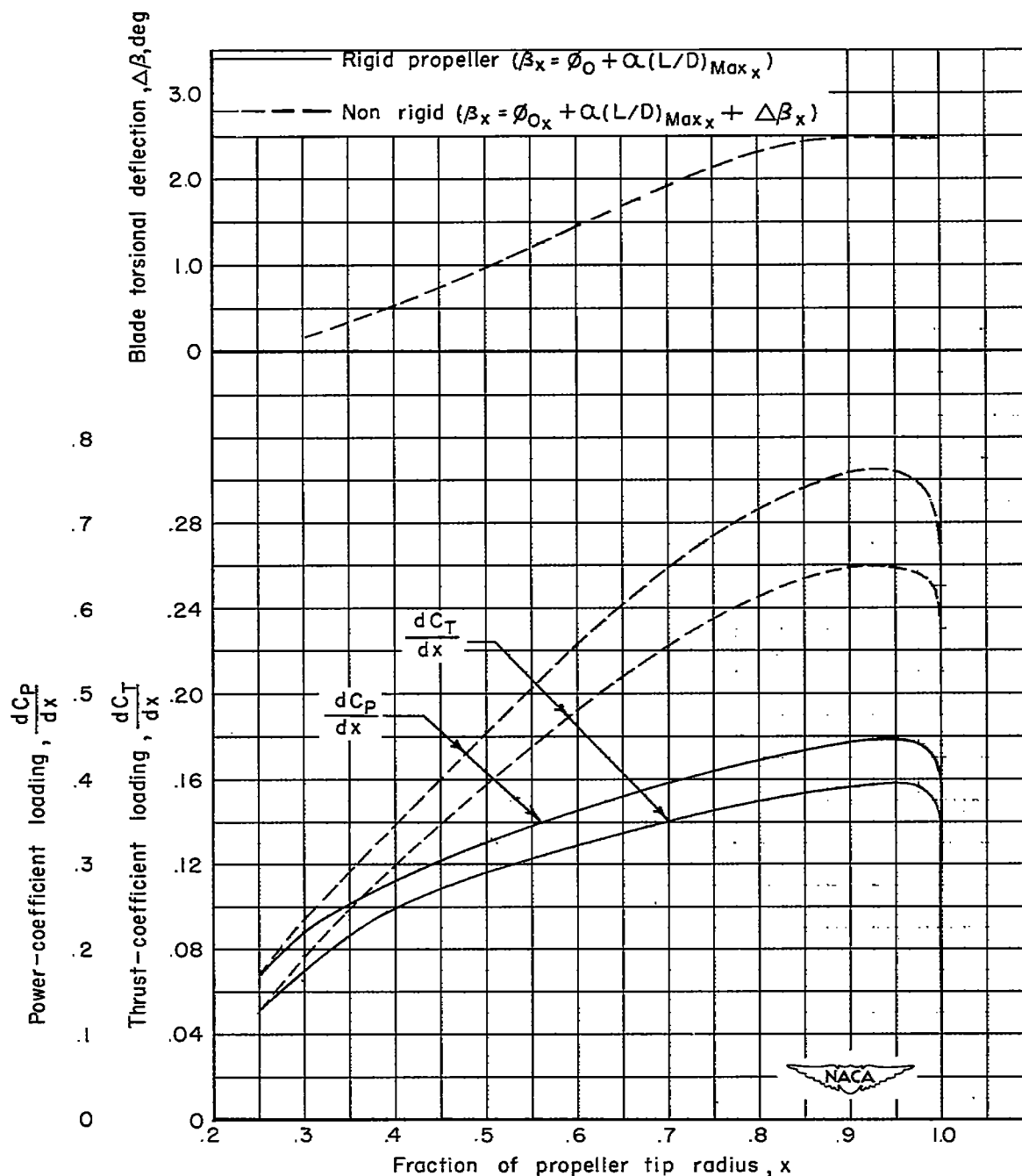
Figure 15.- Effect of blade torsional deflection on the aerodynamic characteristics of the WADC-Aeroproducts propeller considering the propeller as rigid in one case and free to twist for another case. M = 0.95; J = 2.20; rotational speed, 2,100 rpm.